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Re-examining pluton emplacement processes: Discussion

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IN A recent review, Paterson & Fowler (1993) showed how estimated volumes of displaced wall rock are smaller than pluton volumes, and how the widths of strain aureoles around natural plutons are considerably narrower than in models of diapirs where spheres rise through Newtonian fluids (Cruden 1988, Schmeling *et al.* 1988). They then argued that mechanisms other than ductile flow of the wall rocks were necessary to account for these observations. Although I accept that several mechanisms may act simultaneously and change in importance as plutons are emplaced, I argue here that: (i) the displaced volumes of wall rocks may be underestimated because of difficulties in assessing the shape and size of the three-dimensional flow cell in the wall rocks caused by pluton emplacement; and more importantly (ii) the narrow strain aureoles may result from diapiric rise of plutons through power-law rocks and/or result from the effects of thermal softening of the wall rocks.

Several field studies have measured the width of the strain aureole caused by pluton emplacement (see Guglielmo 1993a, Paterson & Fowler 1993, and references therein). The measured width depends on three main factors: (i) The finite strain of the wall rocks, which depends on the velocity field imposed by the diapir. This in turn depends on the diapir's mechanism and depth of emplacement, and on the rheology and physical boundaries of its wall rocks. The longer a rock volume is submitted to a particular strain rate (velocity field), the larger is its strain. The velocity of flow decreases with distance from the contact of rising spheres, so that strains have to accumulate a long time to be distinguishable from any background strain. (ii) Late deformation will mask the strain aureoles of pre-tectonic plutons, while interference with regional tectonic strains will affect the width of the aureoles of syn-tectonic plutons (Guglielmo 1993b). (iii) The measurable width of the aureole depends on distinguishing the strain due to the pluton from regional strains of any age (Paterson & Fowler 1993). This distinction becomes increasingly more difficult as strains are spread over larger volumes, decreasing away from the pluton (as discussed by Guglielmo 1993b).

Laboratory experiments indicate that rocks behave as power-law fluids with exponents n between 2.5 and 5 (Hansen & Carter 1982, Kirby 1983, Wilks & Carter 1990). The power-law exponent n of a viscous fluid is a measure of the sensitivity of its viscosity–stress (or strain-role). For $n = 1$ (Newtonian fluid) the viscosity is constant for any strain rate. For $n > 1$ the fluid softens with increased strain rate. The strain-rate dependency of the viscosity of power-law fluids has important effects on the velocity and flow patterns of the ambient fluid around rising spheres (or diapirs)—and therefore the width of their strain aureoles (Crochet *et al.* 1984, Kawase & Moo-Young 1986, Weinberg & Podladchikov in press). In the following discussion, the difficulties in determining the volumes of rock displaced by diapir emplacement are first considered. The effect which power-law rocks might have on the width of the strain aureole is then discussed, and finally the possible effects of thermal softening of the wall rocks by the diapir are examined.

ROCK VOLUMES DISPLACED BY DIAPIRS

Paterson & Fowler (1993) studied horizontal shortening in strain aureoles around plutons and then integrated shortening to three dimensions around plutons of different shapes. The amount of shortening they obtained for several natural examples only accounted for about 30% of the volume of the plutons. They argued that this volume difference implies that other mechanisms such as doming of the roof, stoping, assimilation and rigid translation of wall rock must have operated at the same time as viscous flow of the wall rock.

However, this discrepancy may largely be due to difficulties in measuring small pluton-related strains beyond the obvious strain aureole, and difficulties in determining the shape of the flow cell around the pluton. The width of the strain aureole around a rising sphere depends on the power-law exponent n of the country rocks. It is widest in Newtonian fluids and narrows as n increases. However, even in the case of rocks with high n

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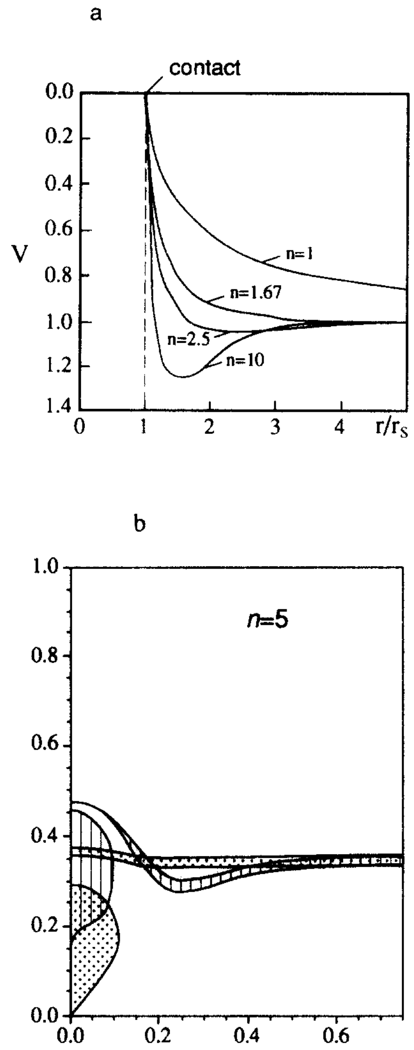

Fig. 1. (a) Velocity of the ambient fluid in relation to a solid sphere as a function of distance from the sphere contact (from Crochet *et al.* 1984). The velocity is given as the difference in velocity between sphere and fluid, divided by the same difference at infinity: $V = (V_{\text{sph}} - V_{\text{obs}})/(V_{\text{sph}} - V_{\infty})$. At the sphere's surface there is no slip of the fluid and the velocity is zero. The overshooting of the velocity profiles observed for $n > 1.67$ indicates that the fluid moves down in relation to a fixed external marker. This results from a decrease in the volume of the disturbed fluid; (b) two steps of a two-dimensional numerical calculation, showing the downward flow of a power-law fluid ($n = 5$) surrounding a rising diapir, causing a passive marker to fold into a synform. The diapir and wall rock have equal effective viscosity. In Newtonian ambient fluids, the passive marker would be dragged upwards by the diapir without developing a synform. The box margins are reflective boundaries and the distances are dimensionless.

values, deformation extends to distances of several radii away from the diapir (Fig. 1a). The small strains furthest from the diapir are important for space considerations because of the large volume of rocks they affect (as admitted by Paterson & Fowler 1993 and discussed by Guglielmo 1993a). Thus, Bateman's (1985) attempt to include far-field deformations in volume considerations similar to those of Paterson & Fowler (1993) is necessary to estimate the displaced rock volume.

Even if small strains far from the pluton *could* be measured and taken into account, integration of shortening measured in a two-dimensional horizontal plane around the pluton to three dimensions is not a simple matter. For example, in isoviscous rocks, shortening is more intense directly above a rising diapir than on its flanks (Cruden 1988), whereas if the pluton is expanding laterally under a rigid top boundary, shortening will be more intense on the flanks than above the diapir. Assessing the displaced volume requires knowing the shape and size of the three-dimensional flow cell around the pluton. This means knowing the temperature distribution, the geometry (physical boundaries) and the rheological properties of the system. The shape of a flow cell around a rising pluton is, for example, considerably different from that around a pluton expanding only laterally beneath a rigid boundary. In both cases, the flow cell may involve parts of the crust, especially the hot, low viscosity, lower crust.

In reality, determining the geometry of the flow cell is an impossible task given the limitations of field data. Although volume estimates derived by integrating shortening measured in a single horizontal plane are a useful first approximation of volumetric relations that could constrain the rheology and geometry of the flow, these estimated volumes are in practice bound to be smaller than the volume of the plutons that displaced them. By themselves, disparities in volume do not automatically imply other emplacement mechanisms.

NARROWING OF STRAIN AUREOLES BY STRAIN-RATE AND THERMAL SOFTENING

The viscosity of a power-law fluid decreases with increased strain rate. The high strain rate immediately around a sphere creates a region of low viscosity where flow concentrates (Kawase & Moo-Young 1986, fig. 1). Figure 1(a) plots the velocity of the ambient fluid along the plane of symmetry (equatorial plane) of the sphere, against distance from the sphere's contact. The velocity is given as the difference between the velocity of the sphere and that of the fluid, normalized by the difference of the far-field velocity in relation to the sphere ($V = V_{\text{sph}} - V_{\text{obs}}/V_{\text{sph}} - V_{\infty}$) and the distance is normalized by the sphere's radius. Figure 1(a) shows how velocity (and therefore strain) is more evenly distributed over larger volumes as n decreases. Another important aspect of Fig. 1(a) is the overshoot of the velocity when $n > 1.67$ (clearly observed for $n = 10$). This overshoot indicates that the relative velocity between fluid and sphere is higher than the ascent velocity of the sphere, and that fluid in the overshooting region moves downwards faster than that further away from the sphere. The downward flow around such spheres would fold a horizontal passive marker into a synform (Fig. 1b). The sense of shear measured along the marker changes from 'diapir up' close to the contact, to 'diapir down' further away. The exact position of the hinge of the synform is a function of the n value of the ambient rock, the viscosity contrast between diapir and wall rock, and the vertical position in relation to the diapir. Marsh (1982) showed that a similar downward flow occurs in thermally

Table 1. Distance from the centre of a solid sphere where the velocity attains 0.99 the value of its long range value (from Crochet *et al.* 1984)

n	1	1.25	1.67	2.5	5	10
r/r_s	30.9	14.4	3.6	1.7	1.2	1.1

softened Newtonian fluids flowing around rising spheres. A concentric synform, wider than the thermal aureole, formed around the granite in Northern Arran during its emplacement (England 1992). The narrow thermal aureole suggests that strain-rate softening of power-law fluids, rather than thermal softening caused the folding.

In order to discuss the implications of the velocity profiles in Fig. 1(a) for field observations, assume that strain is measurable in the field to a distance where the velocity of the deforming wall rock reached 0.99 of the far-field velocity. The width of the strain aureole in rocks of n between 2.5 and 5 would be 45–150 times narrower than in Newtonian rocks (Table 1). Taking the Ardara pluton as a natural example, the width of the strain aureole is approximately 0.16 radii (Paterson & Fowler 1993, their fig. 10). If the minimum strain related to the Ardara pluton could also be measured in Newtonian rocks, the aureole would be only 14 times wider (and not 45 to 150; see their fig. 10). In other words, the strain aureole in the Ardara pluton could be even narrower than it is without conflicting with the strain aureoles around experimental spheres rising through power-law fluids. In fact, contrary to Paterson & Fowler's (1993) argument, it becomes necessary to explain why the aureoles are not narrower than observed. Several explanations can be suggested: (a) perhaps the assumption that strain is observable to the limit of 0.99 of the far-field velocity is incorrect, and strains can only be measured to where the velocity is, say, 0.8 of the long range velocity (Fig. 1a); (b) a low viscosity sphere would cause smaller contrasts in the width of the strain aureoles of power-law and Newtonian fluids; and (c) the n value of the wall rock is smaller than 2.5. The discussion above also applies to the Bass Lake pluton but with different values.

Thermal softening of the wall rock due to heat released by a diapir also concentrates strains to narrow aureoles even in Newtonian wall rocks (the hot-Stokes models of Marsh 1982, Daly & Raefsky 1985, Mahon *et al.* 1988). Marsh (1982, his fig. 1) showed a vertical velocity profile around a hot sphere in Newtonian fluids similar to Fig. 1(a) ($n = 10$). The concentration of strain is similar to power-law models in Marsh's hot-Stokes models, but due to thermal softening instead of strain-rate softening. The width of the strain aureole in hot-Stokes models depends on the value of the Peclet number, Pe. This measures the rate of advection to diffusivity of heat ($\mathrm{Pe} = Vr/k$, where V is the sphere's velocity, r its radius and k thermal diffusivity of the ambient fluid). Daly & Raefsky (1985) showed that when advection is more important than diffusivity ($\mathrm{Pe} > 100$), strain extends beyond the limits of the narrow thermal aureole; conversely, if advection is less important than diffusivity and $\mathrm{Pe} < 1$, the thermal aureole widens and there is no significant concentration of deformation. Pe between 1 and 100 are reasonable values for diapiric ascent of magmas through the crust, and in this range deformation becomes concentrated to a narrow thermal aureole around the pluton. Thus, both strain-rate and/or thermal softening of the country rocks could account for the narrow strain aureoles observed.

It is important to note that the narrowing of the deformation aureole does not imply that deformation does not occur beyond this aureole, or that deformation beyond the aureole is negligible. On the contrary, for space considerations the small far-field strains (beyond the measurable aureole) are important because they affect large volumes of rock (discussed in the first part of this paper and in Paterson & Fowler 1993, p. 203).

CONCLUSION

Accurate estimates of the volume of rocks displaced by ductile flow around plutons require the impossible task of knowing the three-dimensional shape of the flow cell around the pluton, and knowing the small strains beyond the obvious strain aureole. The three-dimensional shape of the flow cell depends on the pluton's radius, on the viscosity variation in the wall rocks (both due to strain-rate dependency and temperature variations) and on the geometry of physical boundaries, such as top rigid boundaries or the presence of other rising diapirs. Shortening measured on the horizontal plane is a practical measure of the shape of the flow cell, but it cannot be integrated to three dimensions with confidence. Although the narrow widths of strain aureoles obvious around plutons could be due to the simultaneous activity of different emplacement mechanisms as discussed by Paterson & Fowler (1993), it could more easily be taken as evidence of strain-rate and/or thermal softening of the wall rock during diapiric emplacement of the pluton. Thus, both the discrepancy observed between two-dimensional shortening (integrated to three dimensions) and the volume of the pluton, and the narrow aureoles do not necessarily imply that other mechanisms were active simultaneously with ductile flow of the wall rock and diapirism.

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